A Numerical Platform for Simulation-Based Exploration of Integrated Behavioral Economic Dynamics

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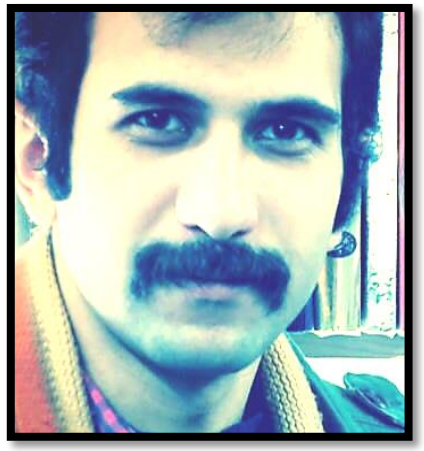

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General Problem

- Many economic challenges are dynamic: decisions today affect our options tomorrow
- It is very difficult to model ***rational*** actors in a dynamic framework with more than, say, 3 decision variables
- Now model the decision maker's psychology at the same time????
  - Quickly becomes intractable

General Problem

- Behavioral economists have modeled multiple psychological influences
- People
  - Are impulsive in the short run but much more patient in the long run
  - Fail to predict how their future selves will differ from their current selves
  - Are overconfident
  - Are paralyzed by fear of losses

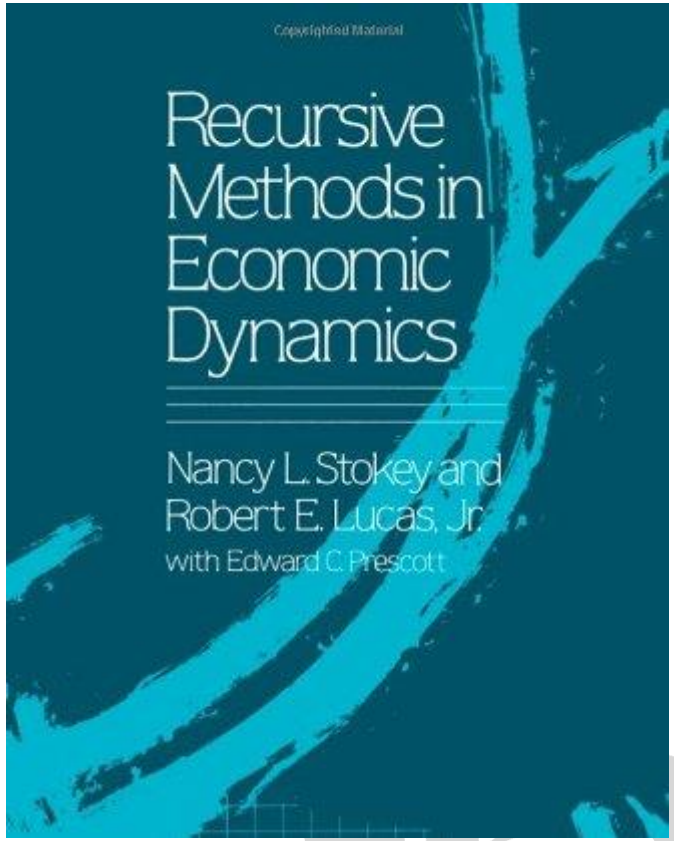
General Problem

- It is really hard to include multiple influences in one model!
- Current leading approach: parsimoniously include one or two general psychological factors, without nuance
  - Benefit: can make progress on broad set of aggregate phenomena
  - Our concern: lose track of interactions between influences

- Recommendation for further reading:

  Stokey and Lucas, 1989, *Recursive Methods in Economic Dynamics*, Harvard University Press, ISBN 0-674-75096-9

  - Assumes you've studied real analysis



Economic Approach to Modeling

- Economics is the study of how people allocate scarce resources
- Economic models are models of allocating resources
- Every actor has something she cares about (profits, utility, etc)
- Specify this as a value function
- OPTIMIZE this value function, subject to constraints

Economic Approach to Modeling

- Elements of an economic model:
  - **Actors:** firms, consumers, regulators….
  - **Payoffs:** profits, utility, social welfare
  - **Actions:** buy or sell different quantities at different prices, invest in new equipment, levy a tax, etc
  - **Constraints:** technology, income, endowment
  - Information
  - **Equilibrium assumption:** some assumption about how actors interact with each other and with nature

Economic Approach to Modeling

- In a dynamic problem, the actor's choices this period influence the actor's constraints next period
- The actor has to judge the consequences of her decision today on her decision tomorrow
- But both her decision today and her decision tomorrow will affect her decision on Sunday
- We assume agents do the best they can with the available information to think through the consequences all the way to the end of time

For today, let’s consider the problem of consumption and saving

Sample Problem

- Each period you inherit a stock of wealth W and you earn income Y
- You can consume and save
  - Liquid or illiquid asset
  - Risky or safe asset
- Consumption(c) gives you this-period utility u(c)
- Saving increases wealth next period
- You want to maximize lifetime utility (the discounted sum of all the this-period utilities)

Sample Problem

- In System Dynamics lingo:
  - Stocks: wealth, lifetime utility
  - Flows: income, consumption, investment returns

- What is the optimal consumption profile?

Sample Problem

- Why consume today?
  - Get utility now!
  - Future utility is discounted
- Why save?
  - Income may go down in the future
  - Even out consumption over time
  - Investment returns
  - Expenses may go up in the future

Biases

- **Present-biased preferences**
  (a.k.a. hyperbolic discounting)

  This creates time inconsistency.
  Think patiently about trade-offs in the future.
  Think impatiently about trade-offs right now.

- Effect on savings:
  Shift savings to the illiquid asset
  Decreases savings

Biases

- **Overconfidence**

  Agents think their market return will be higher than it actually is.

- Effect on savings:
  - Increases savings
  - Shift resources to the liquid (risky) asset

Biases

- **Myopic loss aversion**

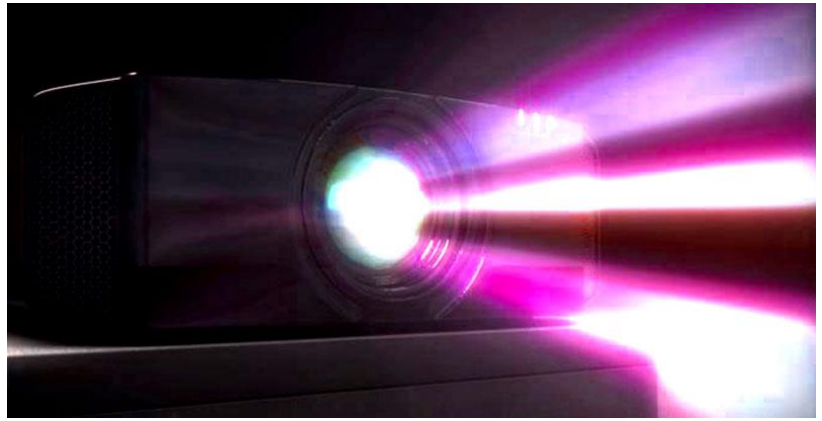
  Agents face a jolt of disutility based on how much their **savings** go down between periods t-1 and t.

- Effect on savings:
  - Shift savings to the illiquid (safe) asset
  - Reduce savings

Biases

- **Projection bias**

  agents expect their future needs and incomes to be similar to current needs



- Effect on savings:
  - Shift savings to the illiquid asset
  - Decreases precautionary saving

Countervailing Biases

- Occur when one class of cognitive bias “offsets” or “compensates” for another
- Exploring Such Joint Biases is the ultimate aim of our work
- Here’s one example
  - *Overconfidence* about investment returns makes someone “Too Willing” to invest in Risky Funds
  - *Fear of Loss* makes someone “Too Unwilling” to invest in Risky Funds

“Individual Welfare Function” Model in Behavioral Economics

Noisy Income
Noisy Investment Income

Liqui ets
Illi Ass

Safe
Risky s

Fully Rational Model

- ***Lifetime Utility (U):*** is the extent of happiness the household derives from its overall consumption
- ***Instantaneous Utility (u):*** how much utility the household gets in a given period by its *consumption (c_t)* in that period
- ***Discount Factor (δ):*** how much less people care about the future compared to the present. (0< δ<1).
- ***Coefficient of Relative Risk Aversion (ρ):*** how much someone dislikes fluctuations in consumption.
- ***Labor income (Y_t):*** what the person receives in each period.

$$Y_t = GY_{t-1}$$

$$U(\{c_t\}) = \sum_{t=0}^{T} \delta^t u(c_t) = \sum_{t=0}^{T} \delta^t \frac{c_t^{1-\rho}}{1-\rho}$$

Optimal Solution

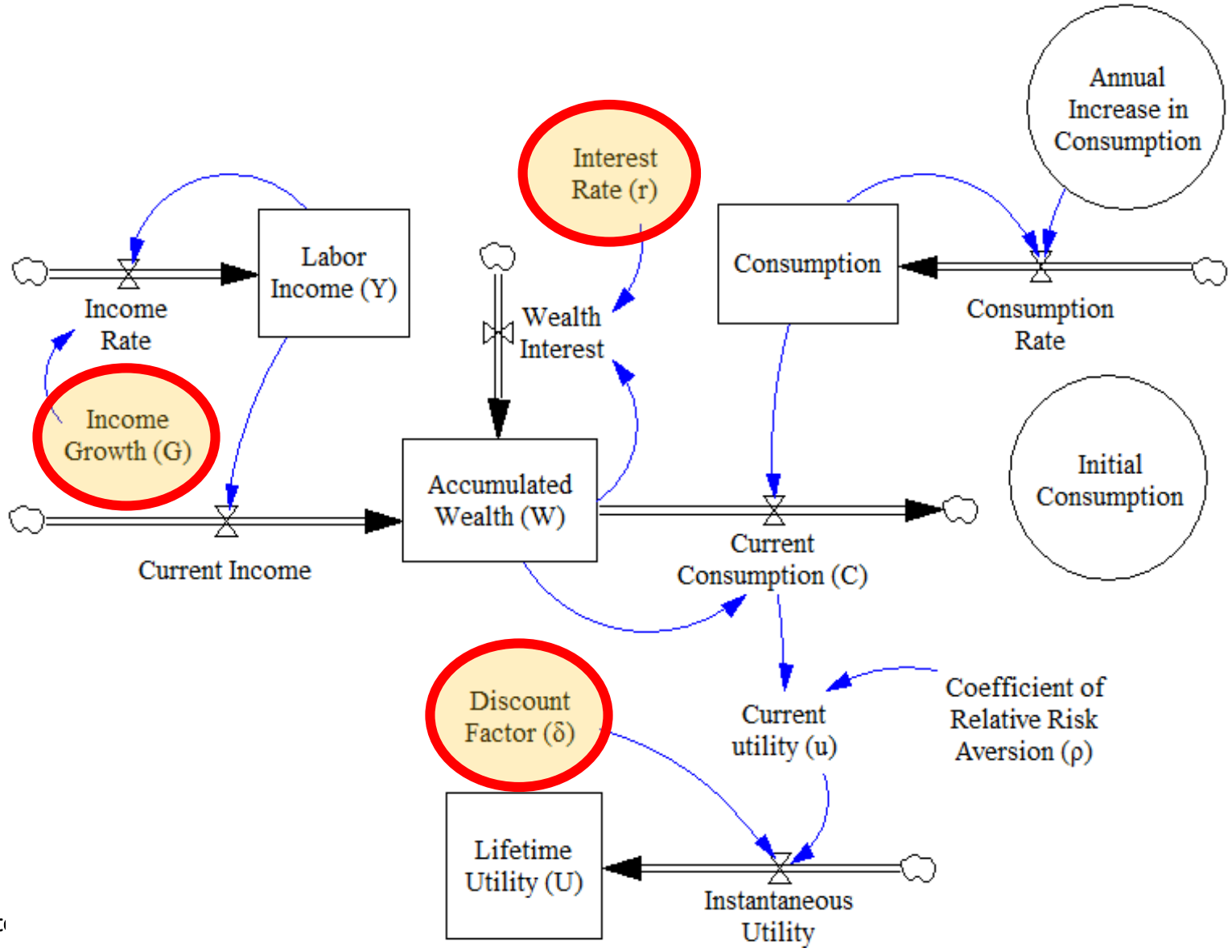
You backwards induct a decision rule about how much to consume each period as a result of inherited wealth.

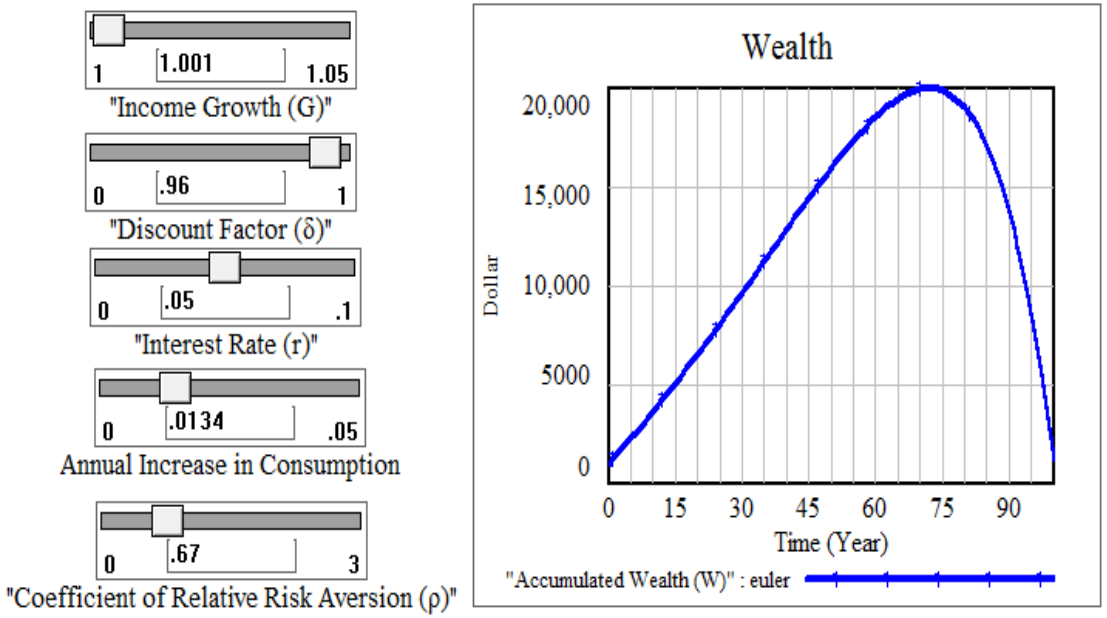
- ***Consumption (c)***
- ***Income Growth (G)***
- ***Discount Factor (δ):*** how much less people care about the future compared to the present. (0< δ<1).
- ***Interest Rate (r)***
- ***Coefficient of Relative Risk Aversion (ρ):*** how much someone dislikes fluctuations in consumption.

$$u'(c_t) = \delta(1+r)Gu'(c_t+1)$$

$$c_t^{-\rho} = G\delta(1+r)c_{t+1}^{-\rho}$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\rho} = G(\delta(1+r))$$


Annual Increase in Consumption
Interest Rate (r)
Labor Income (Y)
Consumption
Income Rate
Wealth Interest
Consumption Rate
Income Growth (G)
Initial Consumption
Accumulated Wealth (W)
Current Income
Current Consumption (C)
Discount Factor (δ)
Current utility (u)
Coefficient of Relative Risk Aversion (ρ)
Lifetime Utility (U)
Instantaneous Utility



In this model, the equation for *Consumption Rate (CR)* is:

$$Consumtion\ Rate = Consumption * Annual\ Increase\ in\ Consumption$$

Using the mathematical equations behind this formulation, we will have:

$$c_{t+1} - c_t = c_t * Annual\ Increase\ in\ Consumption$$
$$c_{t+1} = c_t * (Annual\ Increase\ in\ Consumption + 1)$$
$$\frac{c_{t+1}}{c_t} = (Annual\ Increase\ in\ Consumption + 1)$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\rho}_{simulation} = (1 + Annual\ Increase\ in\ Consumption)^{\rho}$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\rho}_{Simulation} = (1 + 0.0134)^{0.67} = 1.009$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\rho}_{Euler} = G(\delta(1 + r)) = (1.001) * (0.96) * (1 + 0.05) = 1.009$$

"This Vensim Simulation Exactly Reproduces Results using simplified Euler methods"

Use the Platform to Explore All Four Biases

We are working on adding more details to the model starting with the **Present Bias.**

We believe that the interaction between these biases can cancel out or reinforce their effects depending on the settings of the experiment.

Basically, the origin of these biases can be found in the individual's misperception of different variables in the model.

We need more complex model.

Theoretical Elaboration

- We want to conduct several experiments for different scenarios, once we have confidence in the model.
  - Shocks in income, interest rate, etc.
  - Stochastic vs deterministic
  - Finite vs infinite time horizon
  - Competitive vs uncompetitive environments
  - More investment options

- We will also add lessons that we have learned from SD in order to find the behavioral patterns
  - Feedback loops
  - Delays

Our work

- Step one: reproduce this standard economic solution using system dynamics techniques (done)
- Step two: introduce highly parsimonious biases into the system dynamics model (doing now)
- Step three: expand the model to allow
  - More realistic decision environment (e.g. retirement)
  - More generalized decision rule
    - Implementable in system dynamics
    - Capable of modeling multiple biases at once
- Step four: explore model in other domains of application

Next step

- Introduce errors in perception of different parameters
- Map interaction of these errors
  - How does overconfidence in interest rate offset misperception of your personal level of risk comfort?

Misperceiving one Parameter

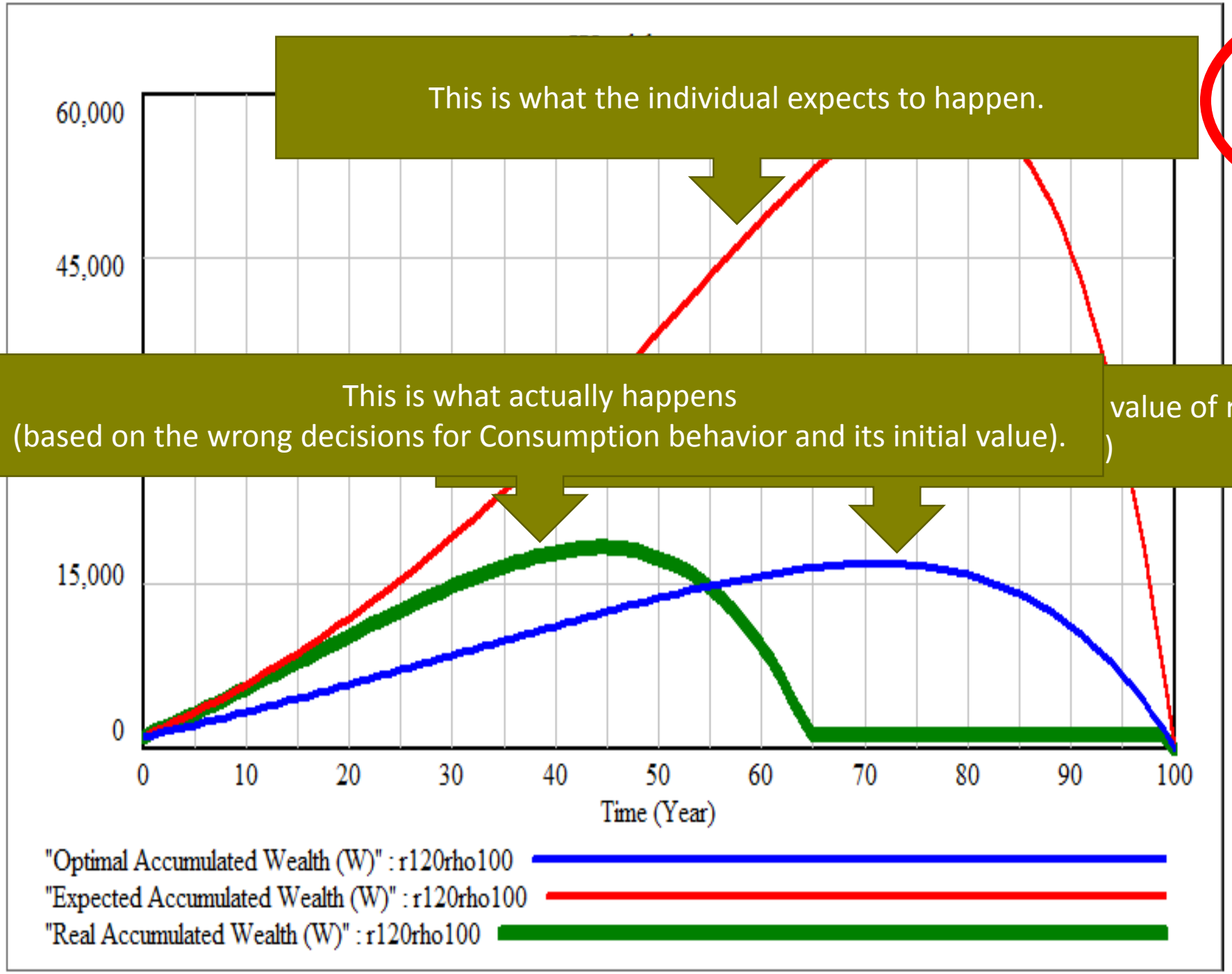
An individual thinks that the Interest Rate (r) is 20% higher than what it really is.

$$r' = 1.2\ r$$

This is what the individual expects to happen.

This is what actually happens
(based on the wrong decisions for Consumption behavior and its initial value).

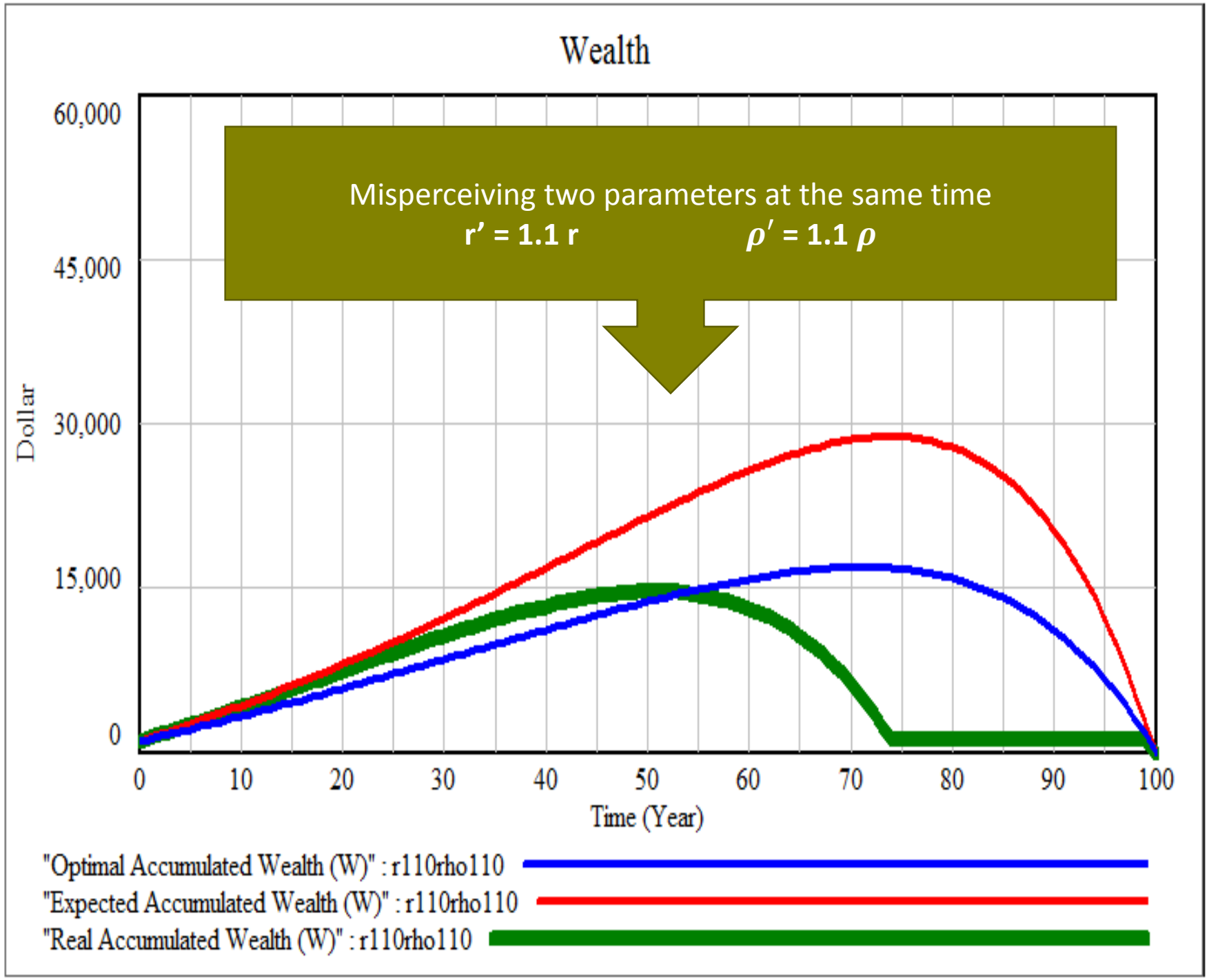
value of r.
)



Time (Year)	100
Actual Annual Increase in Consumption	.02643
Optimal Annual Increase in Consumption	.01196
Actual Initial Consumption	625.8
Optimal Initial Consumption	828.5

Time (Year)	100
Expected Accumulated Utility	694.9
Real Accumulated Utility	669.4
Optimal Accumulated Utility	675.6

Time (Year)	100
"Income Growth (G)"	1.001
"Coefficient of Relative Risk Aversion (ρ)"	.67
"Discount Factor (δ)"	.96
"Interest Rate (r)"	.05
Perception of r	1.2
Perception of row	1



Time (Year)	100
Actual Annual Increase in Consumption	.0174
Optimal Annual Increase in Consumption	.01196
Actual Initial Consumption	750.1
Optimal Initial Consumption	828.5

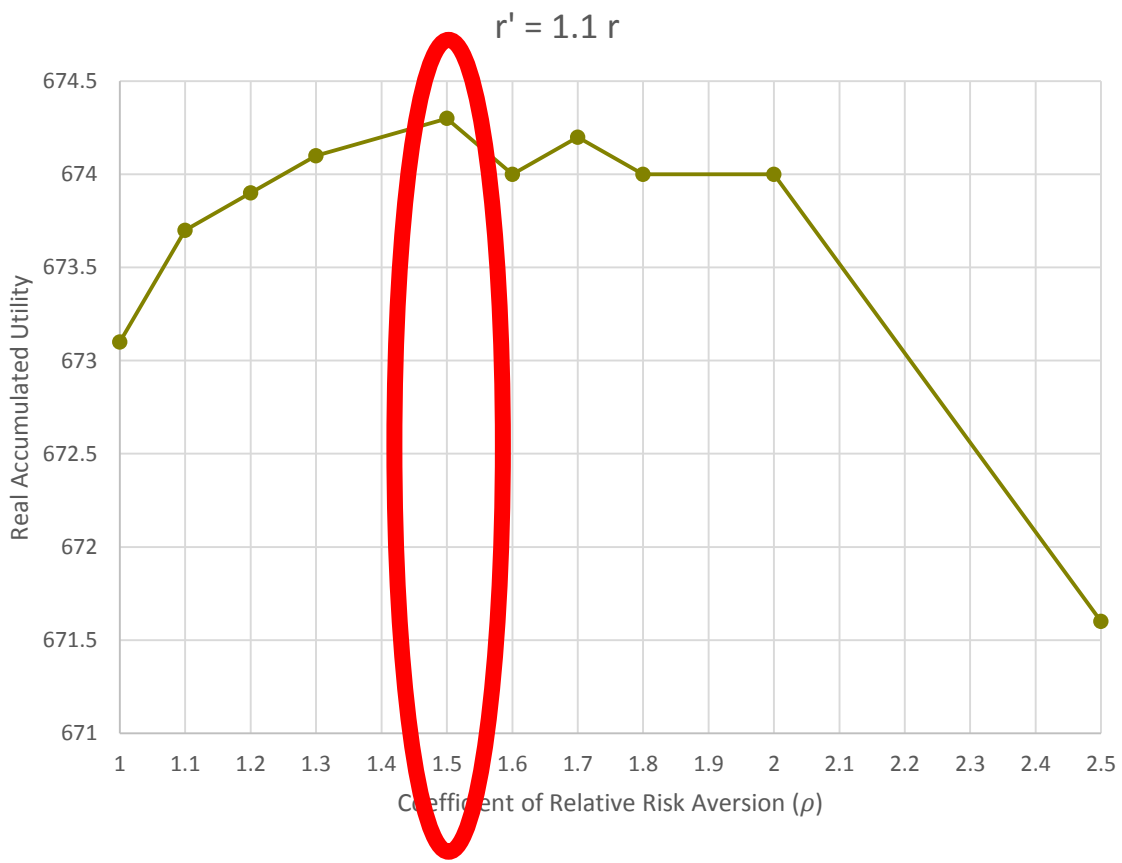
Time (Year)	100
Expected Accumulated Utility	500
Real Accumulated Utility	673.6
Optimal Accumulated Utility	675.6

Time (Year)	100
"Income Growth (G)"	1.001
"Coefficient of Relative Risk Aversion (ρ)"	.67
"Discount Factor (δ)"	.96
"Interest Rate (r)"	.05
Perception of r	1.1
Perception of row	1.1

- We know that sometimes these biases cancel each other out
- If we only consider r and ρ:
- For each value of r' there is a ρ' that can redeems thee impact of r'.

$$\left(\delta(G)(1+r)\right)^{\frac{1}{\rho}} = \left(\delta(G)(1+r')\right)^{\frac{1}{\rho'}}$$
$$\rho' = \log_{(\delta(G)(1+r))}\left(\delta(G)(1+r')\right)^{\rho}$$
$$r' = \frac{\left(\delta(G)(1+r)\right)^{\frac{\rho'}{\rho}}}{\delta(G)} - 1$$

- We experimentally tested it in our simulation and the results are the same.



If r' is given and

$$\delta = 0.96$$
$$G = 1.001$$
$$r = 0.05$$
$$Perception\ of\ r = 1.1$$
$$(r' = 0.055)$$
$$\rho = 0.67$$

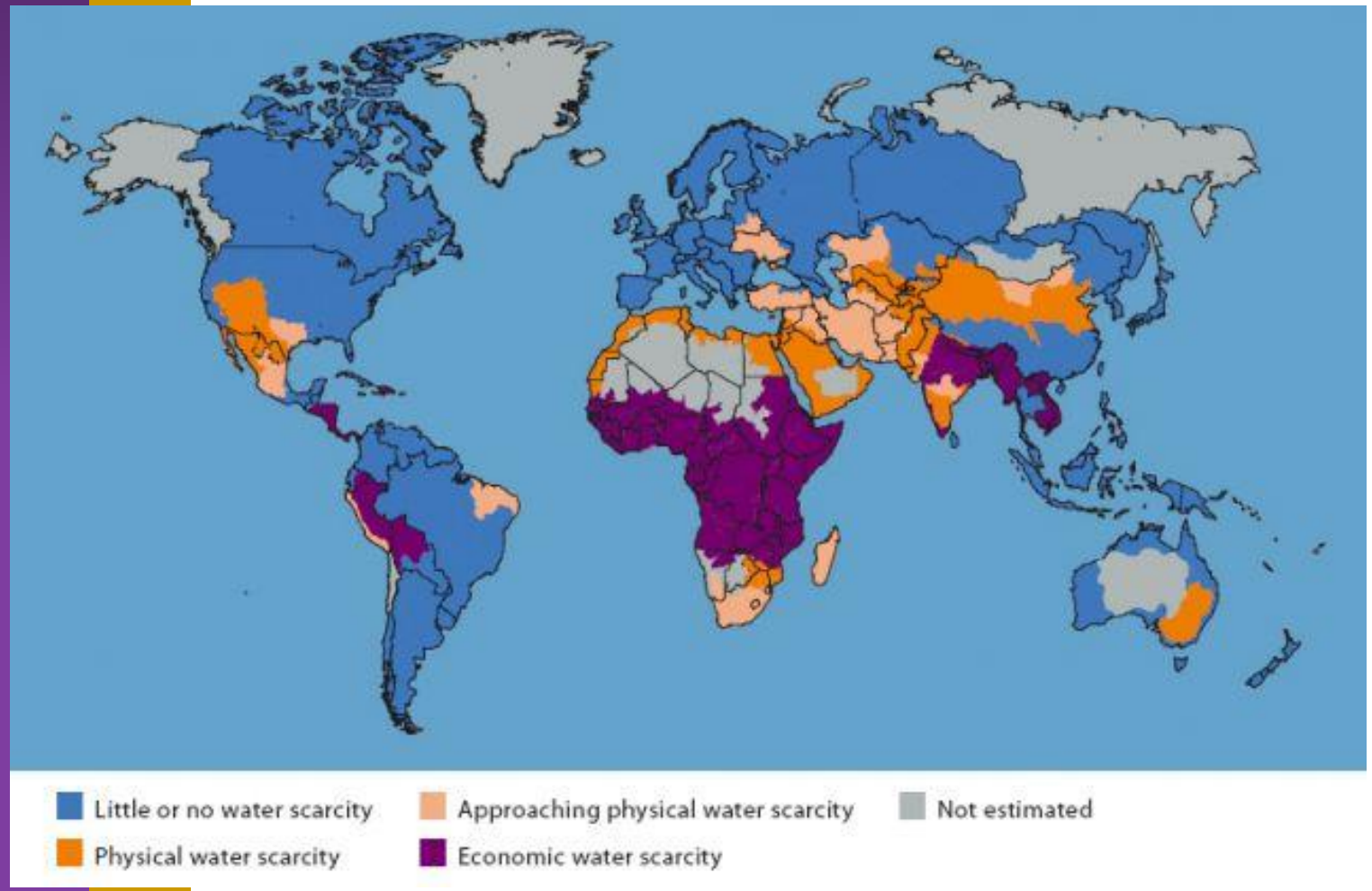
Then

$$\rho' = \log_{(0.96*1.001*1.05)}(0.96 * 1.001 * 1.055)^{0.67}$$
$$\rho' = \log_{1.009008} 1.0138128^{0.67}$$
$$\rho' = \log_{1.009008} 1.0092336$$
$$\rho' = 1.0249296$$
$$\frac{\rho'}{\rho} = \frac{1.0249296}{0.67}$$
$$Perception\ of\ rho = \frac{\rho'}{\rho} = 1.53$$

Applications

- Concepts such as consumption, savings, and utility are mostly used for resource management and planning

- By resources we do not only mean MONEY



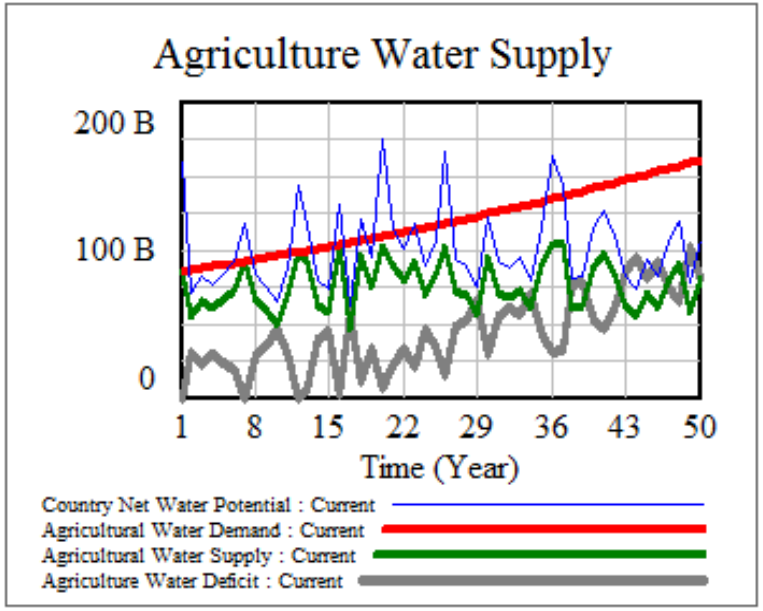
Less than 3% of all the water resources are Fresh.

Together, the Antarctic and Greenland ice sheets contain more than 99 percent of the freshwater ice on Earth.

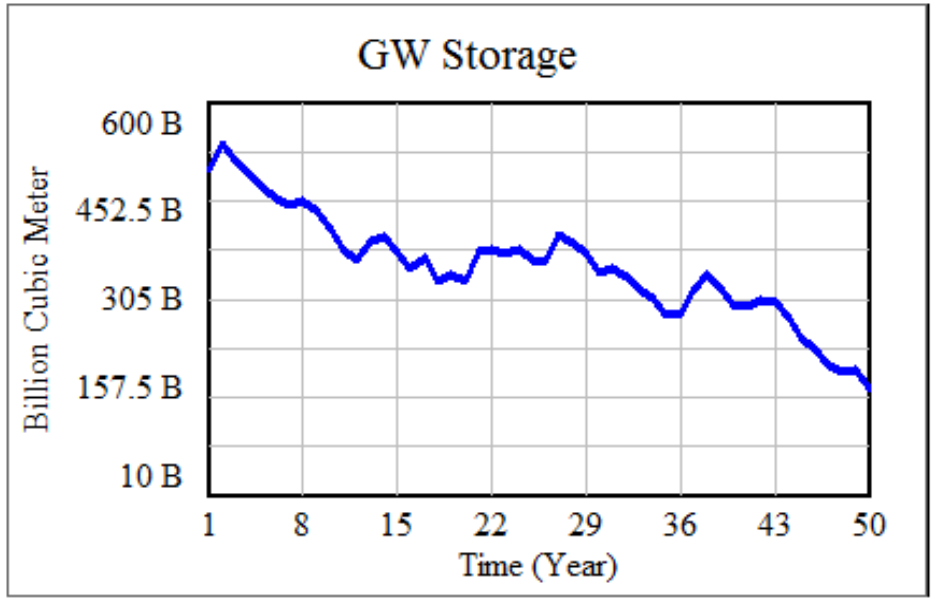
IRAN is in the Economic Water Scarcity phase. It will approach the Physical Water Scarcity by 2025 (World Resources Institute).

Final Results

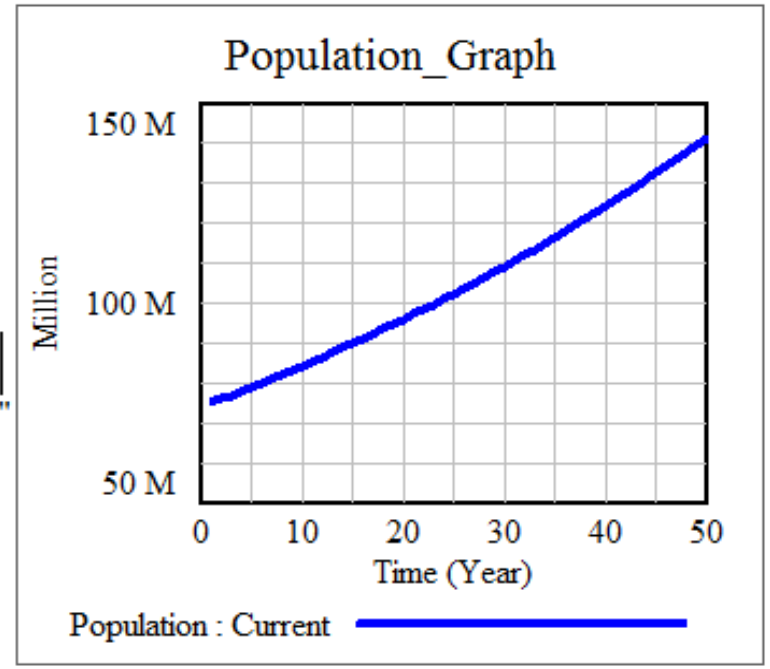
Time (Year)	50
"Ave. Direct Inf. to GW"	25.51 B
Ave SW Rech GW	18.8 B
Ave Ret GW Rech	6.266 B
Ave GW Abstraction	56 B
Ave GW over draft	1.337 B
Ave Ground Water Storage	353.4 B
Last Period of Ground Water Storage	170.1 B



Weighted Non Struc. Para	**0**
Total Weight	**1**
**********	
Dom. Water Dem (L/DCap)	**250**
"Ind. Water Dem. (m3/YCap)"	**15.7**
Food Consumption/Cap/Y	**900**
Water Productivity (Kg/m3)	**.79**



0 [0] 1 Social aspect
0 [0] 1 Cultural
0 [0] 1 Training
0 [.22] 1 weight of SA
0 [.22] 1 "weight of Cul."
0 [.1] 1 "weight of Train."
0 [0] 1 Organization
0 [0] 1 "Dessimination & Propaganda"
0 [0] 1 Technology
0 [.14] 1 "weight of Org."
0 [.08] 1 "weight of D&P"
0 [.1] 1 "weight of Tech."
0 [0] 1 Water Treatmet and Recycling
0 [.14] "weight of Treat."



Water Saving (Dam Con.+Water Tras) Zab	1.2 B
Water Saving (Dam Con.+Water Tras)+ Karun	6 B
Water Saving (Dam Con.+Water Tras)+Sirvan	2.34 B
Water Saving(Pot Water Sup. Net.)	200 M
"Water Saving (Harvesting)"	80 M
Future Conventional Water Production	9.82 B

0 [1 B] 2 B "Dess. Volume Persian Gulf"
0 [400 M] B "Dess. Volume Oman Sea"
0 [200 M] 1 B "Dess. Volume Caspian Sea"

0 [2000] 2000 Investment For Renewable water
.5 [1] 1.5 "Clim.C. on preci Value"

.7 [1.7] 2 Fertility
0 [.54] 2 Mortality
0 [80] 100 Future Life Expectancy

Iran Water Model is developed for evaluation of present and future water resources management in Iran.

1. **Water balance module:** calculates the net renewable water.

2. **Water demand:** calculates consumption per capita and return water ratios.

3. **Population**

4. **Waste Water, treatment ratio and water dilution demand**

5. **Nonstructural measures:** includes Social, Cultural, Training, Dissemination and propagation, Organization and management, Technology, Water treatment and recycling.

6. **Investment on Structural Water Development Projects:** will reduce water loss due to low efficiency in irrigation network, water transfer system, potable water network and evaporation

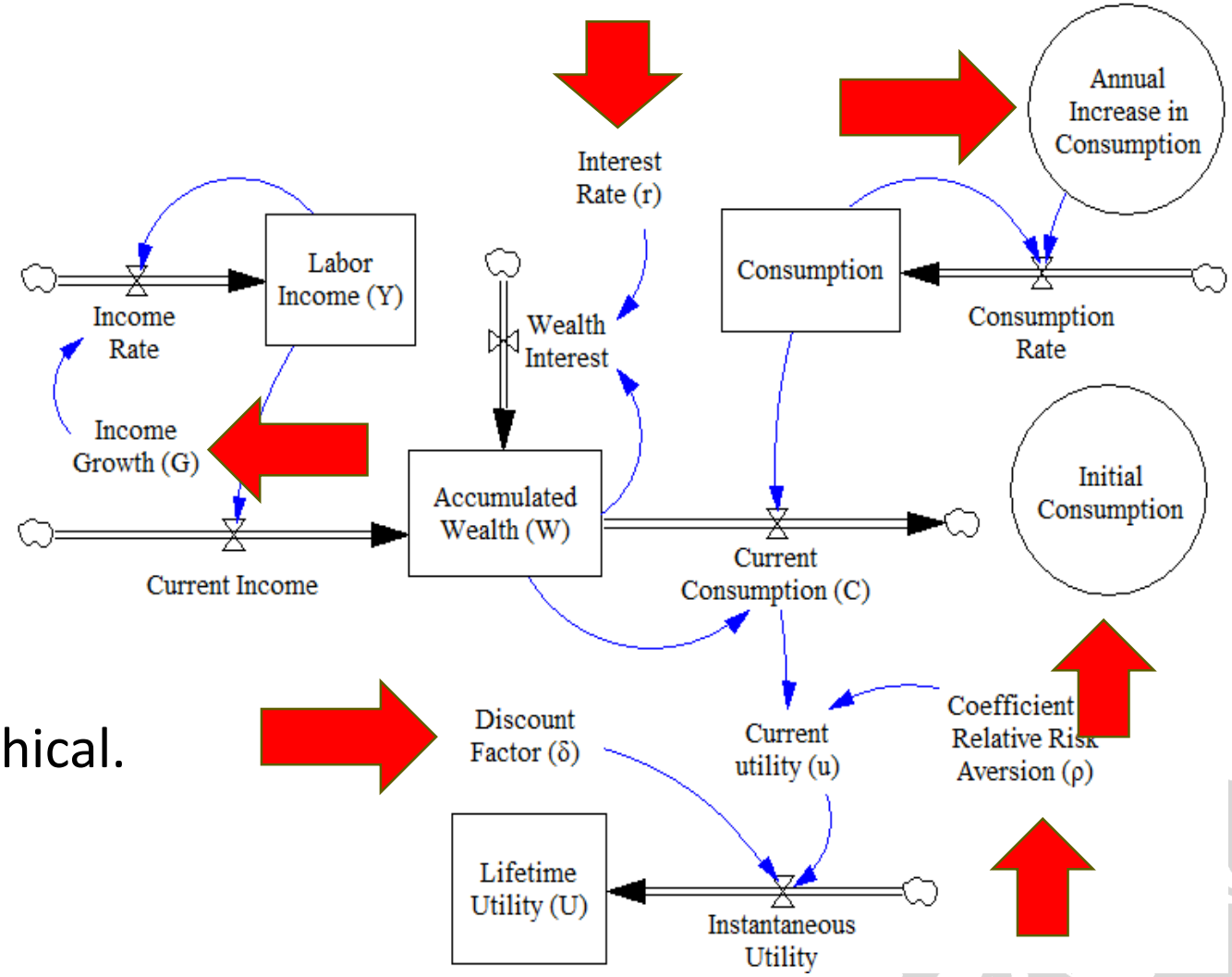
7. **Water Desalination**

Our model represents
One individual,
One agent,
One company, or
One generation...

With Specific Settings

Without interaction with others.

This is wrong and sometimes unethical.



Inter-Generational Optimized Use

Externalities

Our Generation

DELAY

Our future selves
Our Children

Let’s Talk About This!

Are there other works connecting SD to economic dynamics?

How we can optimize our model in different time steps?

What do we need to explain more clearly?

Are you aware of other applications?